RNEDE: Resilient Network Design Environment

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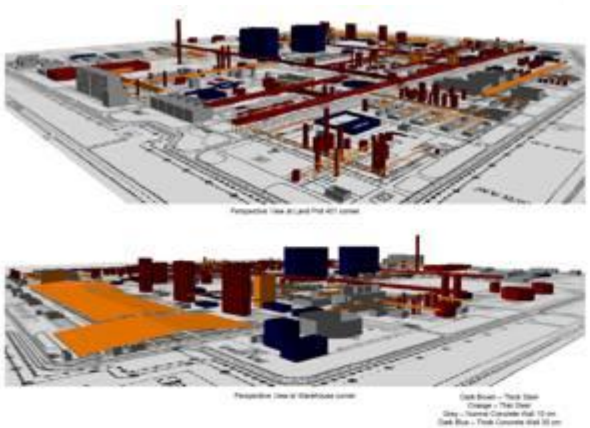
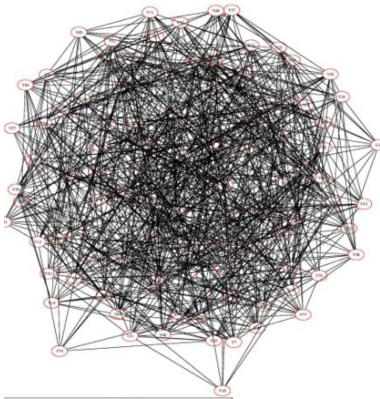
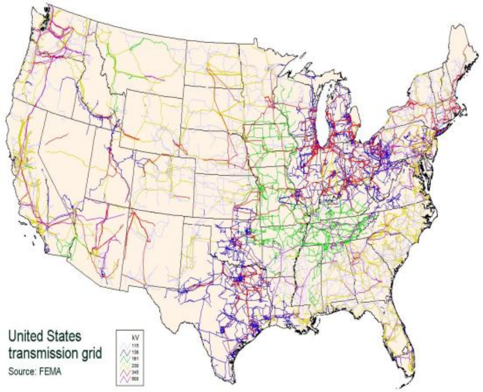
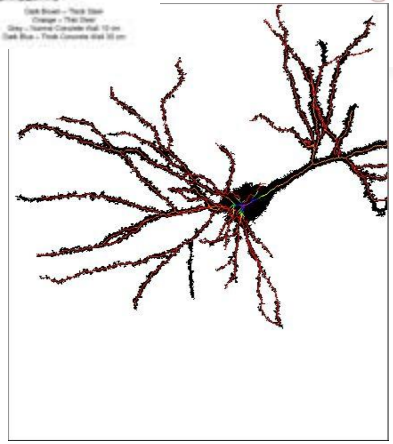
Motivation

- The nation's critical infrastructure is increasingly characterized by large networks
  - electrical power grids
  - road and airline systems
  - biological pathways
  - chemical plants
  - Internet









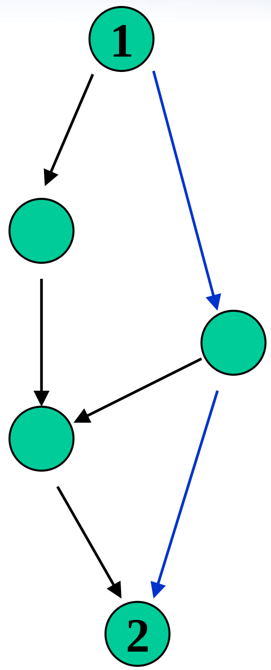
Problem: Design of Resilient Topologies

- Topology governs operational efficiency and resiliency
- How to optimize topology in the event of threats and disruptions?
  - Which remedial action must be taken?
  - Where in the current network remedial actions should be taken?
  - Whether remedial actions are even worth taking?

Efficiency of interaction

- Distance:
  - d (i, j) = length of the *shortest* path between i and j
- Average Path Length

$$\langle d \rangle = \text{Average APSP} = \frac{\sum_{i,j} d(i,j)}{\frac{n(n-1)}{2}}, \quad 1 \le i,j \le n$$



- Interaction Efficiency
  - "Time or Effort" required for an exchange between agents i and j
  - Measured by Path length
  - Smaller average path length, higher efficiency

$$Eff = \frac{1}{\langle d \rangle}$$

Robustness of Interaction

- Failure of one or more nodes/edges
  - *Structural* robustness:
    - Number of resulting component(s)
    - Resulting graph connected: perfectly robust
  - *Functional* robustness:
    - Efficiency of resulting component(s)
    - Average path length of resulting graph unchanged: perfectly robust
  - *Worst-case* versus *average-case*

Overall Robustness: combination of above

Efficiency and Robustness

- They are often conflicting Objectives
  - Increasing efficiency often implies reducing robustness for the same cost
  - And vice versa
- Efficiency : A measure of short-term performance or survival
- Robustness: A measure of long-term performance or survival

Redundancy and Cost

- MST: e = e_{min} = n – 1
  – No *redundancy* or *excess connectivity*
- CG: e = e_{max} = n(n-1)/2
  – Maximum *redundancy*
- Redundancy coefficient

$$\beta = \frac{e - e_{\text{mst}}}{e_{\text{cg}} - e_{\text{mst}}} \qquad 0 \le \beta \le 1$$

- Structural and Functional Redundancies
- Cost: measure of the economy of design
  – Assumption: All nodes and edges have equal importance
  – Cost per edge = 1, Total cost C = e

Optimization Formalism

- For a given environment α, design a net to maximize survival fitness G

$$\max\ G = \alpha\ \eta_E + (1-\alpha)\ \eta_R - c_1(\beta, k) - c_2(n)$$

η_E is the efficiency

η_R is the robustness

α is a constant, $0 \le \alpha \le 1$

c_1 is the cost function related to the addition of edges

c_2 is the cost function related to the addition of nodes

k is the vertex degree of the node to which a new edge is being added

β is the redundancy coefficient

n is the number of nodes

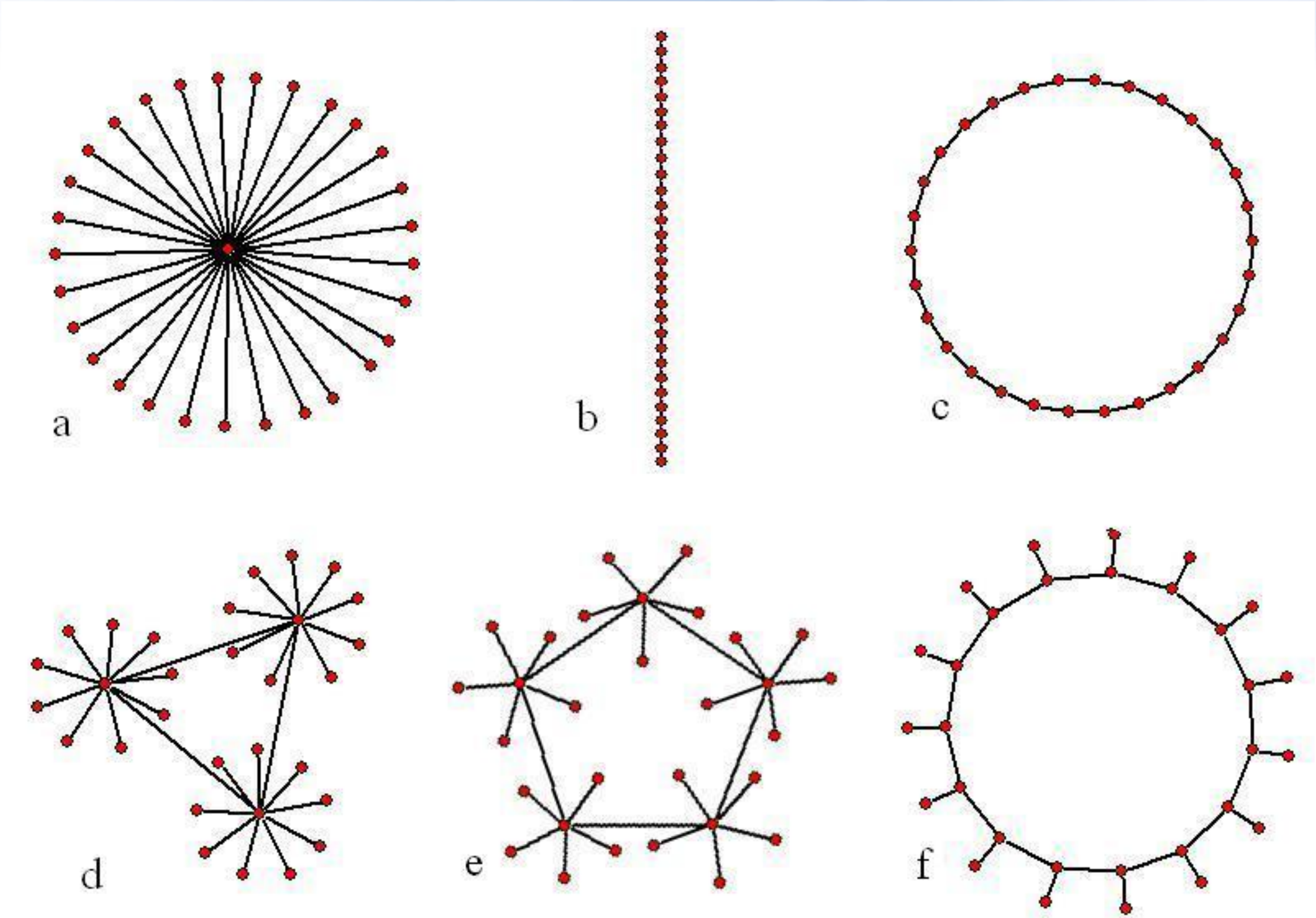
Principle of Maximum Harmony

Harmony Function *G*

Different 'Survival' Environments α

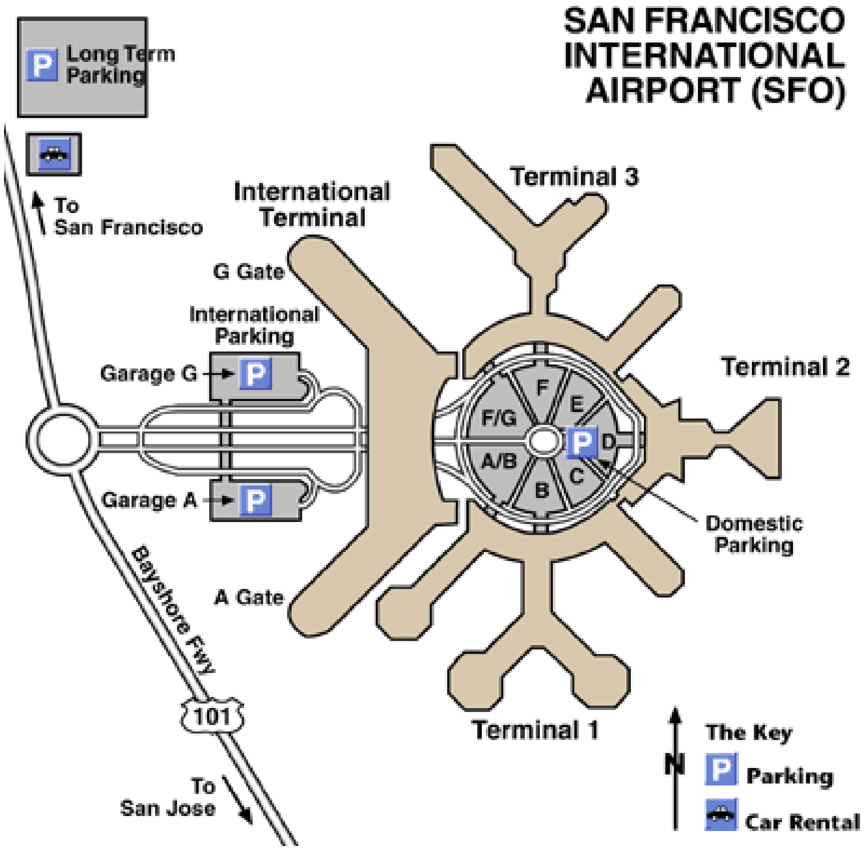
- $\alpha = 0$
  - Only Robustness matters for survival
- $\alpha = 1$
  - Only Efficiency matters
- $\alpha = 0.5$
  - Both matter equally
- Other α values are possible

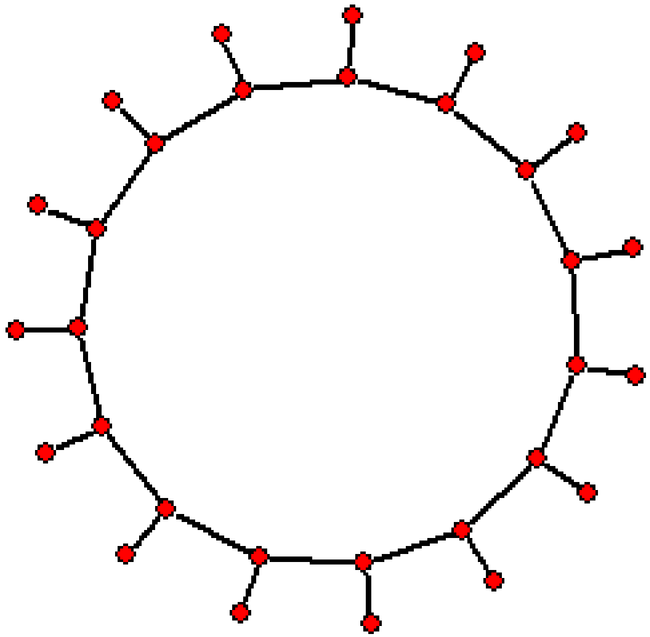
Network Topologies



(a) Star (b) Line (c) Circle (d) Triangular Hub (e) Pentagonal Hub (f) Perfect Hub

San Francisco Airport





Perfect Hub, Alpha = 0.5

RNEDE: Resilient Network Design Environment

RNEDE

- Visualize, Create, Edit and Analyze large complex networks/graphs
- Dynamic simulation platform for the development and evaluation of methods <u>for</u> control of networked systems
- Object Oriented system
- Prototype version in Python

RNEDESim: A Simulator for Resilient Network Design

- Key Features
  - Replays various threat and disruption scenarios
  - Suggests various remedial options
  - Provides a visual guide of the network
  - Scalable for large networks consisting of thousands of nodes and edges
  - Application-independent

A Formal Description

- Topology $T = (V,E)$
- T satisfies set of constraints $C = \{c_1,\ldots,c_n\}$
- Cost function for maintaining T, $S : T \rightarrow R^+$
- Set of incidents (disruptions), $I = \{i_1,\ldots,i_n\}$
- Compromised topology, $T' = (V',E')$ or (V, E') or (V',E); May not satisfy C
- Amount of compromise: $F: (T, T') \rightarrow R^+$
- Set of remedial actions, $A = \{a_1,\ldots,a_n\}$, and a cost function, $Q: A \rightarrow R^+$

Resilient Control of Topology

Obtain a set of remedial actions such that the compromise is minimized

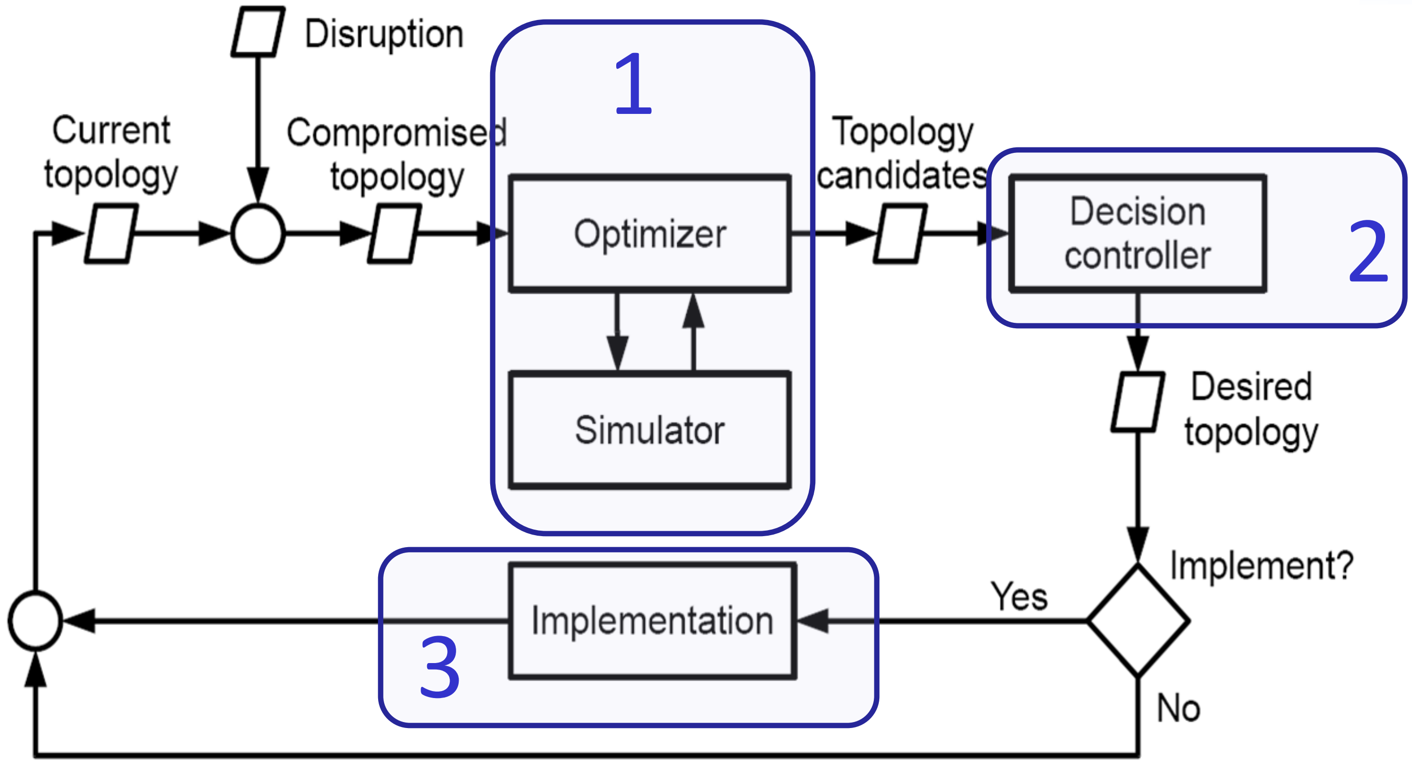
i.e., $F(T'', T) < \epsilon$

Given the disruptions, minimize the cost of maintaining the compromised topology and the cost of making the change

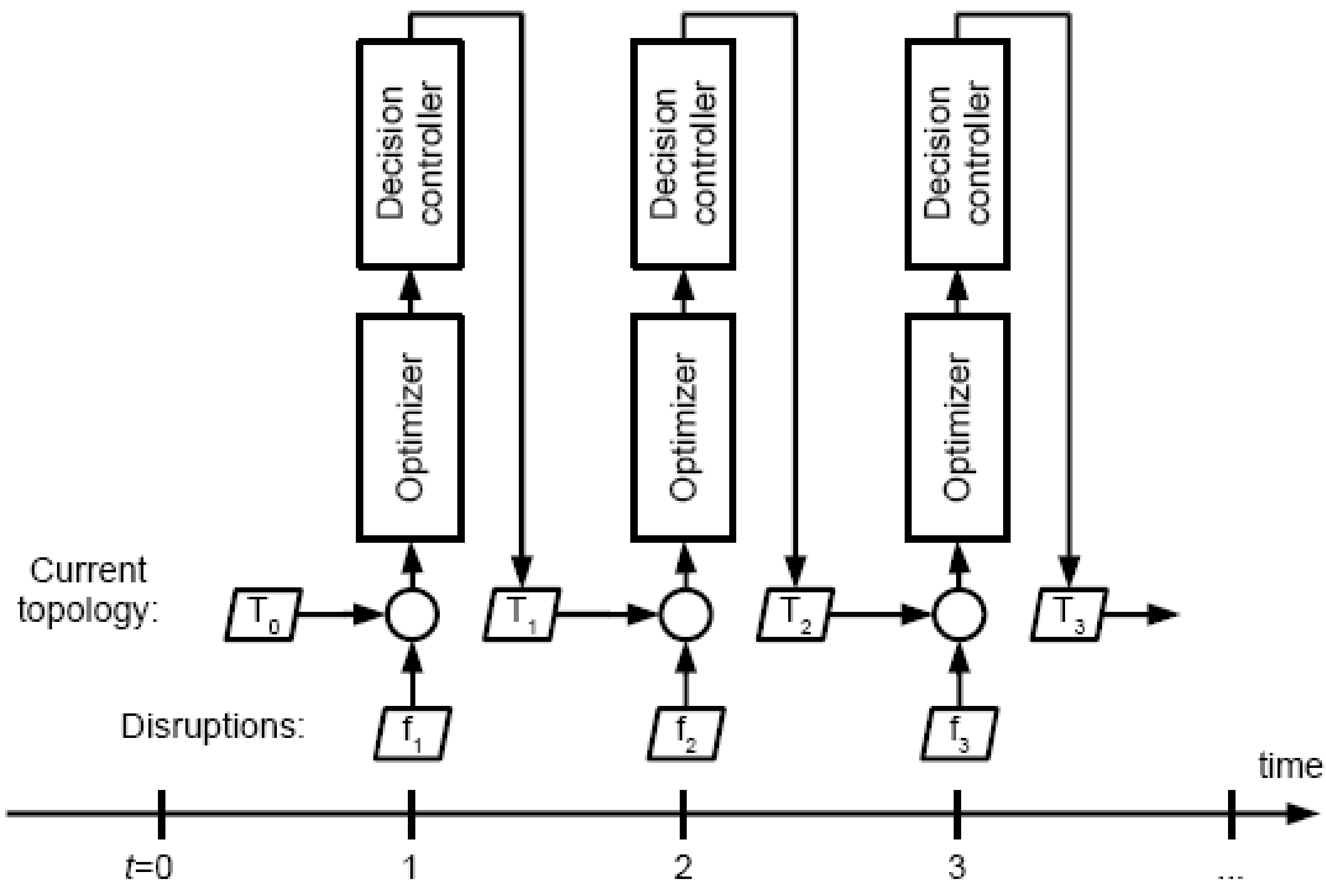
Optimizer and Simulator

- Optimizer: Minimizes the difference in the value of the objective function, *F*, on the original topology and the compromised topology by choosing a set of remedial actions
- Simulator: Given a network specification, it calculates the value of the objective function *F*

RNEDE Architecture



RNEDE In-Action

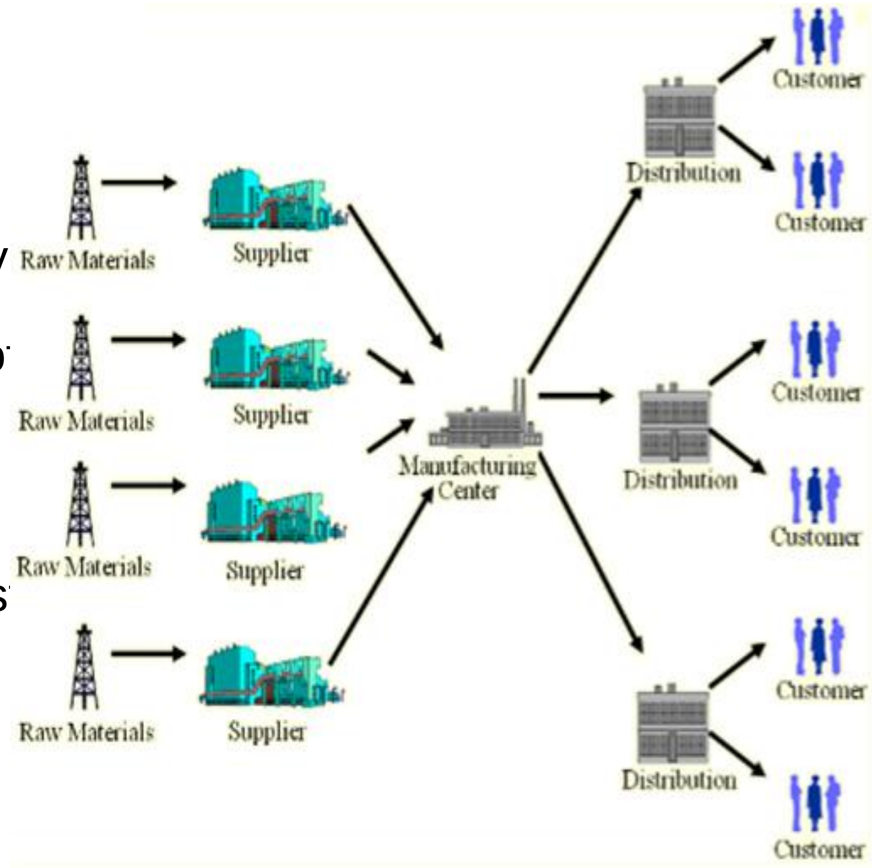


Decision-Controller

- Determines if it is beneficial to transition to T'' or remain in T'
- The decision is based on
  - the incoming sequence of disruptions,
  - the transition cost
    - associated with remaining in the current topology and the cost of transitioning between T' and T''.
- Adopts a rent-vs-buy model
  - staying in the current topology corresponds to renting and moving to another topology corresponds to buying
  - Several known algorithms, greedy and worst-case.

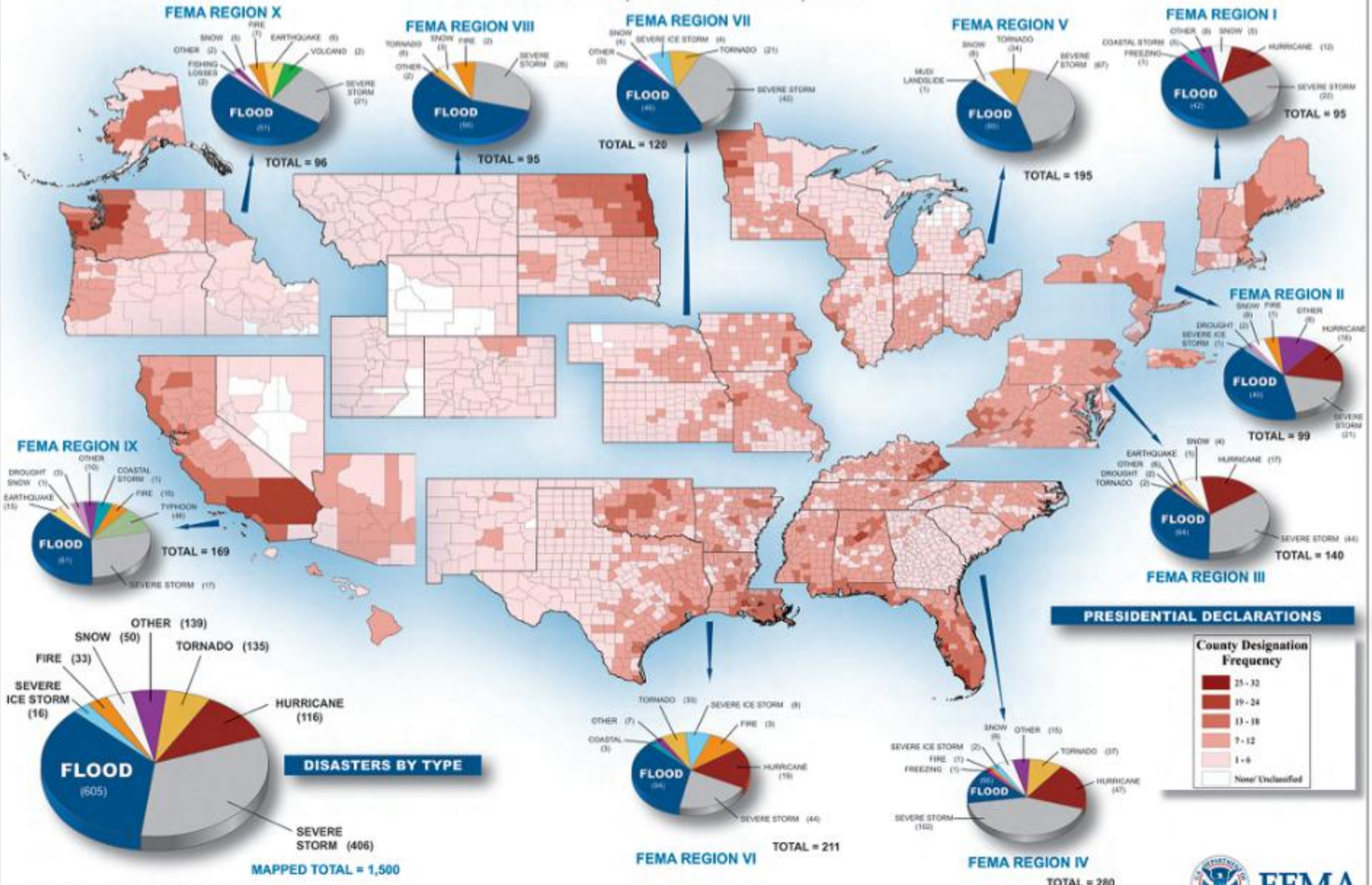
A Case Study: Supply Chain Networks

- Supply chain involves both flow of physical products and information
- Conventional objective for supply chain network design is optimizing efficiency (fulfillment o[f] objective with minimum cost)
- A crucial objective is the maximization of robustness: the ability of the supply chain to resis[t] shocks



PRESIDENTIAL DISASTER DECLARATIONS

December 24, 1964 to March 3, 2007



* Prior to December 24, 1964, 179 declarations did not have county designations. Therefore, of the total declared disaster (1,500), only 1,321 are included in the Mapped Total.

FEMA

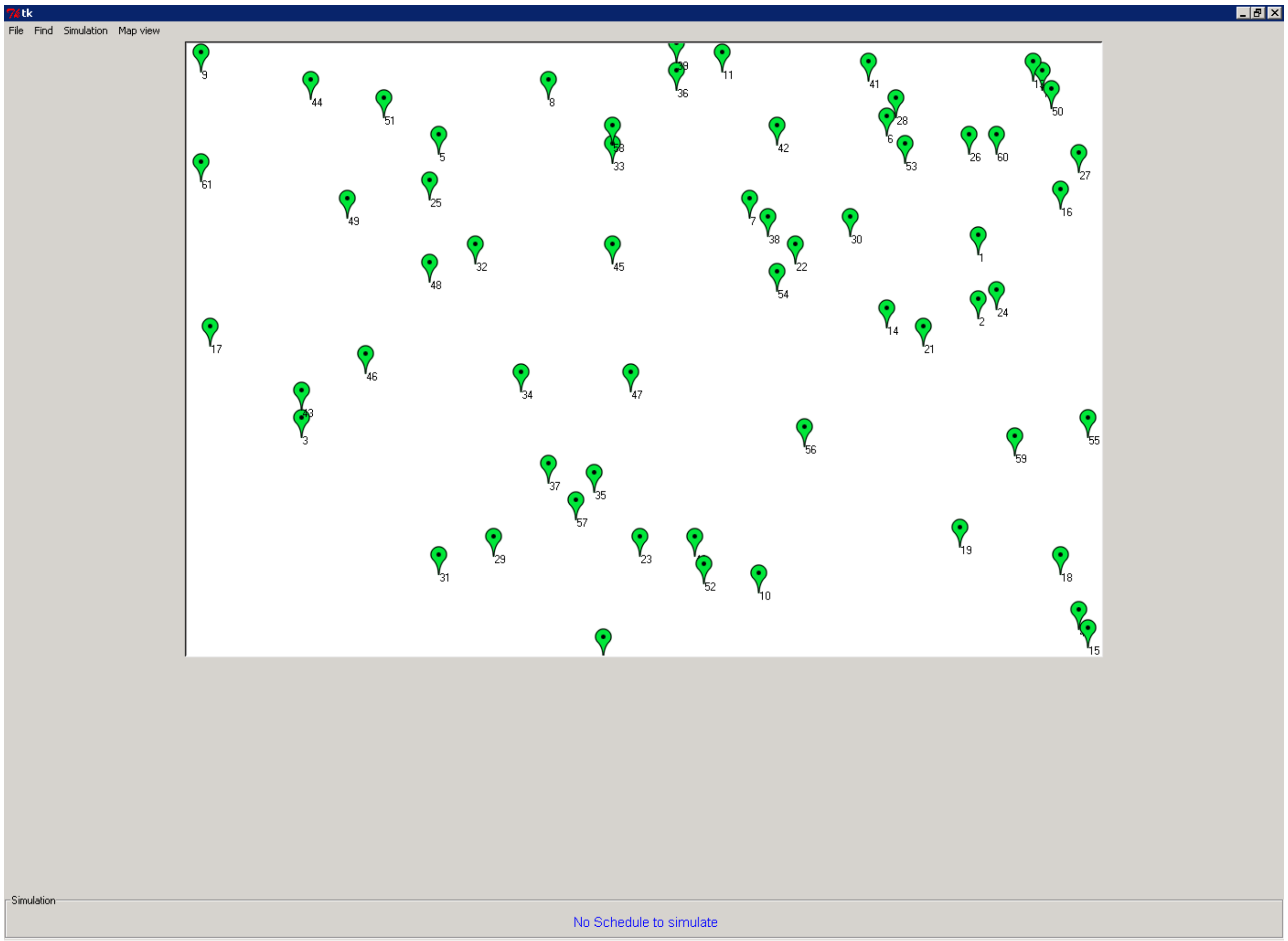
Supply Chain Data

- 1 Manufacturing Centre in Detroit
- 50 Customer Zones (US States)
  - Delivery to State Capitals

- 10 candidates for warehouse locations:
  - One in each FEMA region
  - Boston, NYC, Philadelphia, Jacksonville, Chicago, Houston, Kansas City, Denver, LA, Seattle

- Demand for each state proportional to the state population
- The distance between the manufacturing centers, warehouses and customer zones is road distance from Google^{TM} Maps

RNEDESim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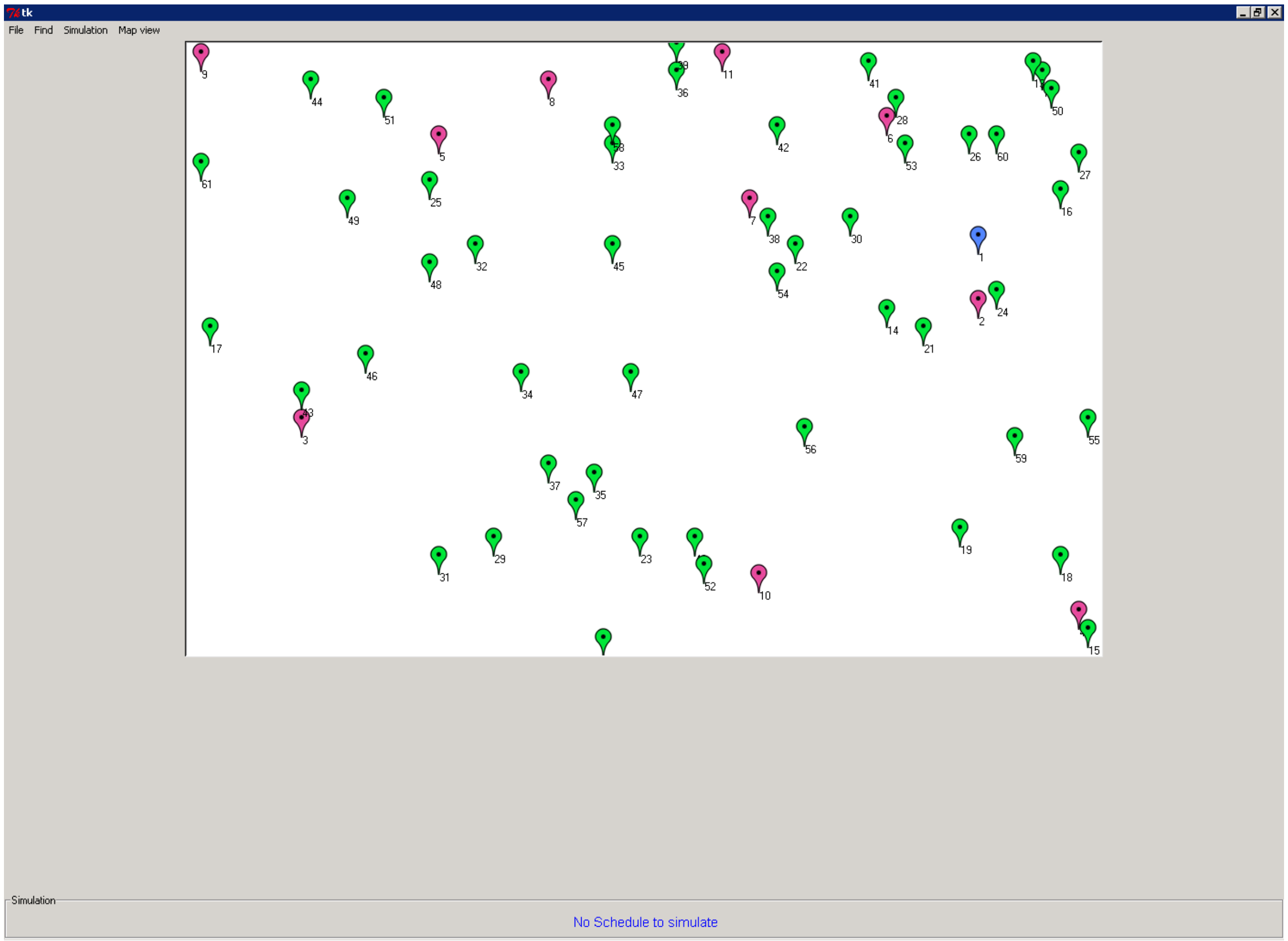
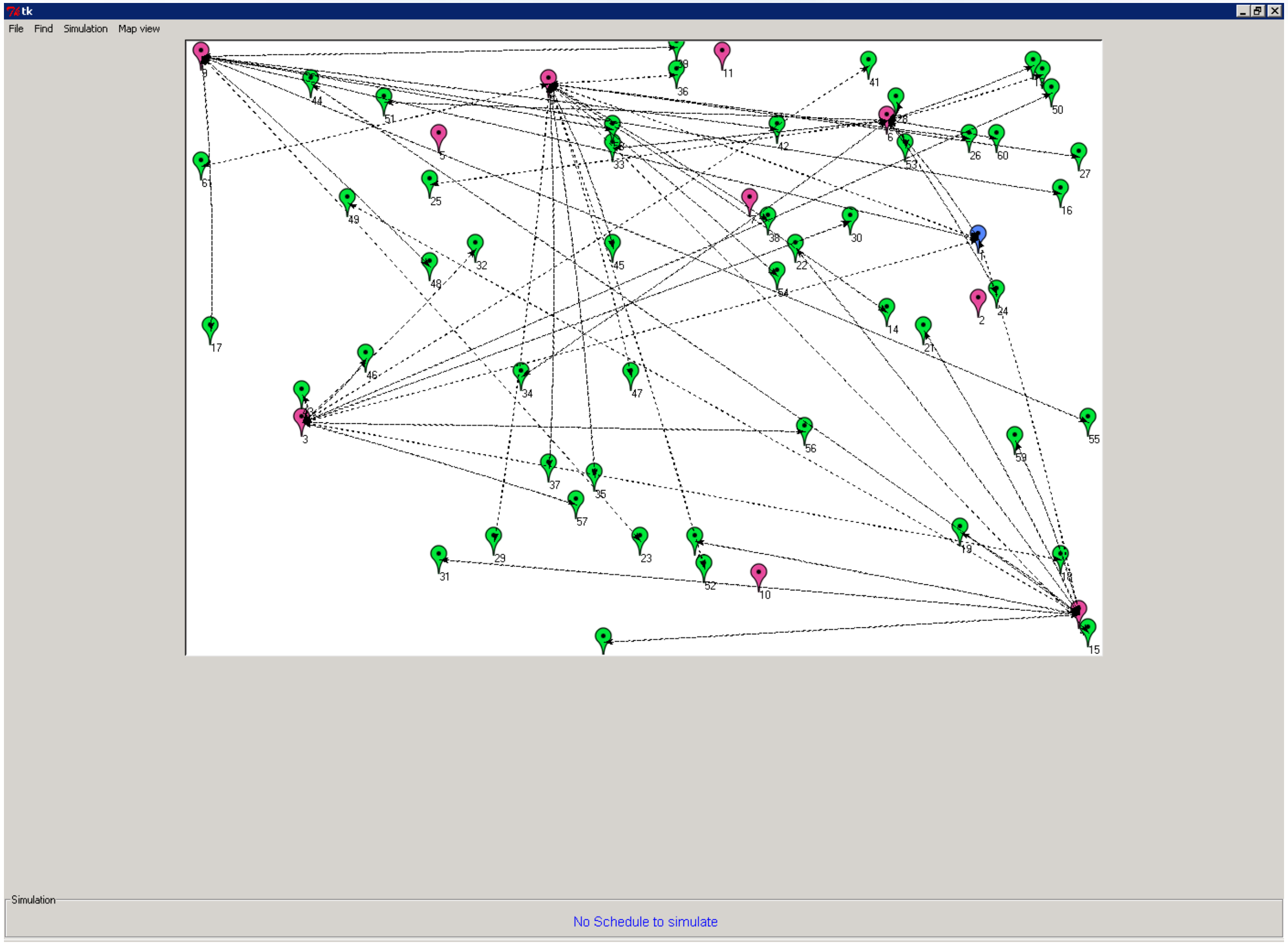
Find
Simulation
Map view
Simulation
No Schedule to simulate

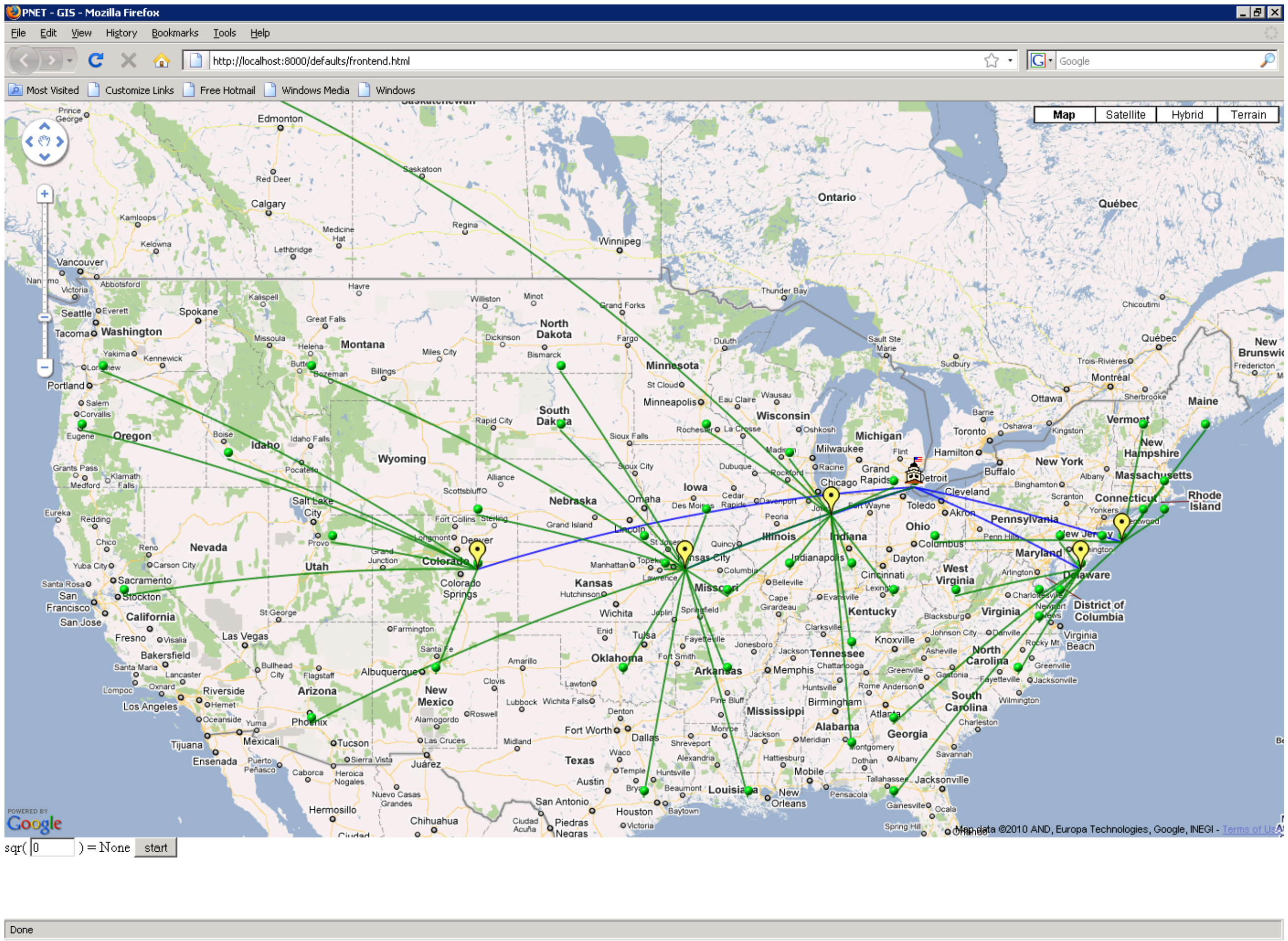
RNEDESim: Producers/Consumers



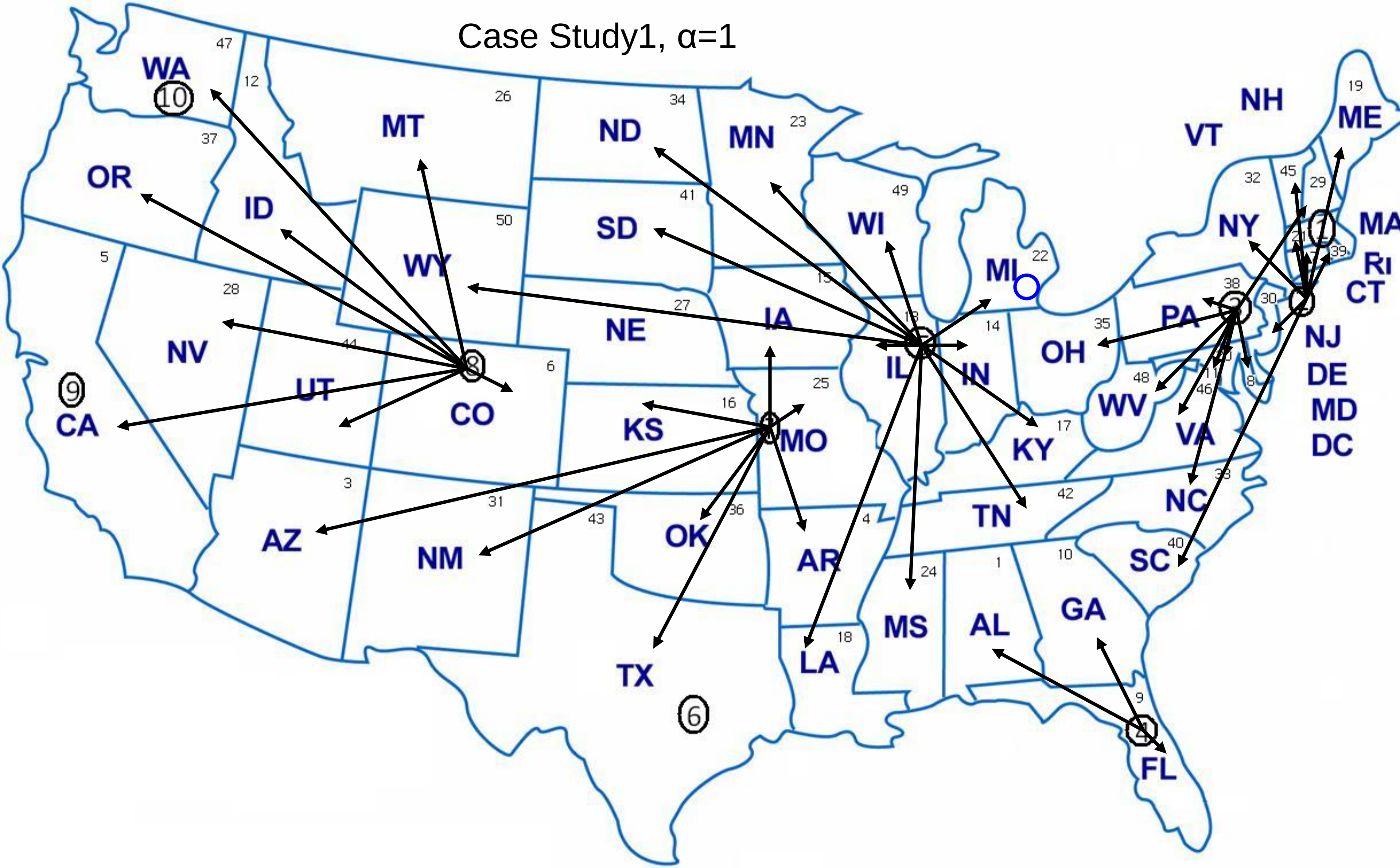
RNEDESim: Optimized



RNEDESim: View on the Map

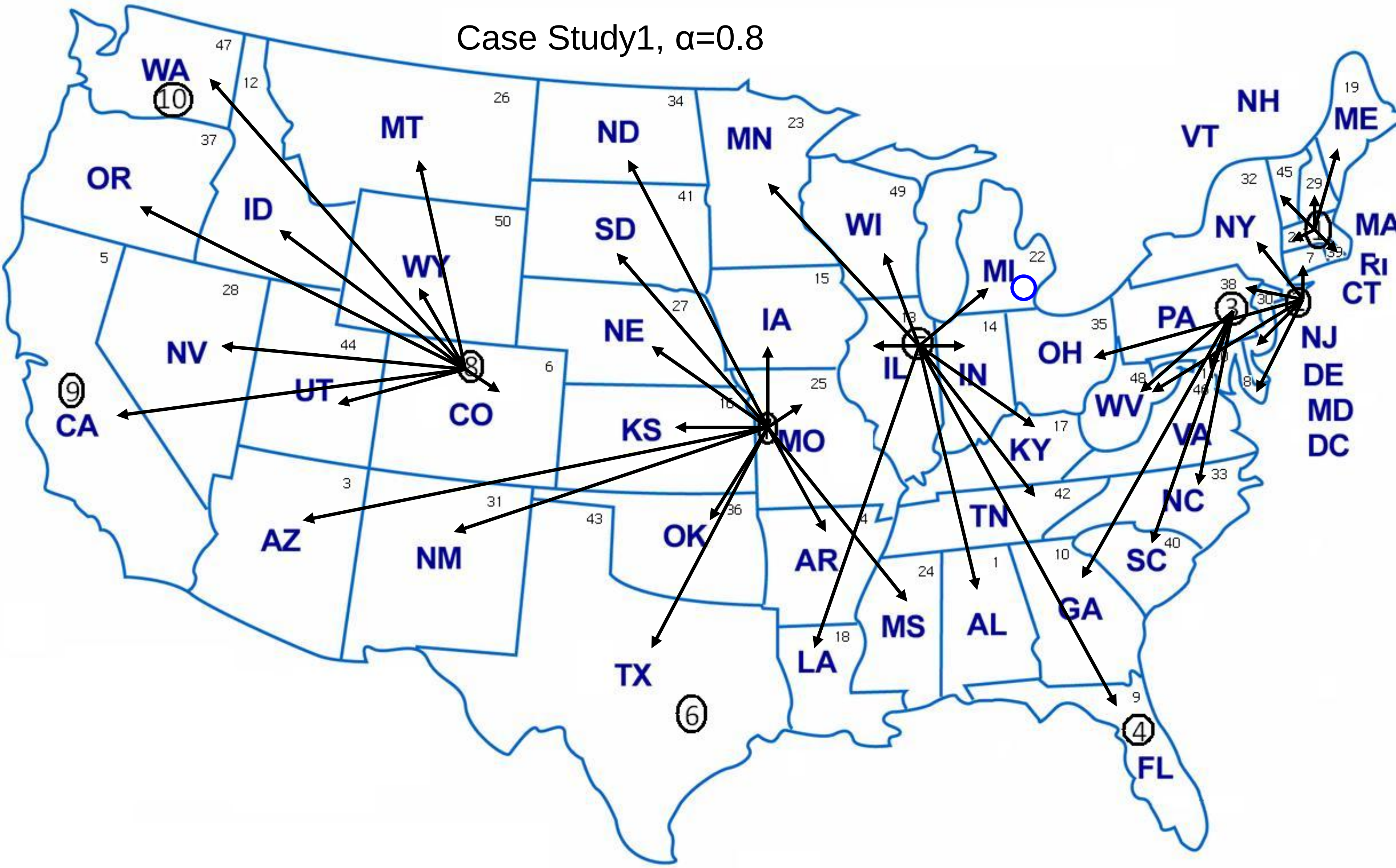


Case Study1, α=1



Jacksonville	Houston	Chicago	Los Angeles	Philadelphia	Kansas City	New York	Seattle	Boston	Denver
12.49%	9.41%	8.70%	7.54%	6.33%	5.35%	4.42%	4.28%	4.24%	4.24%

Case Study1, α=0.8



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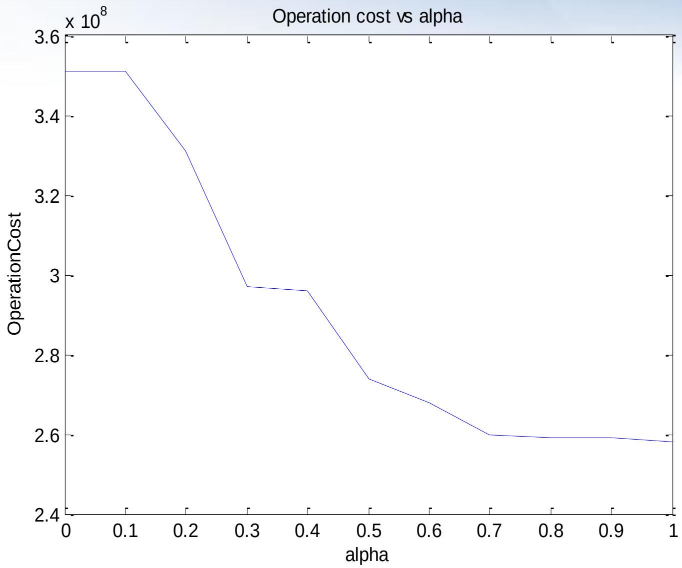
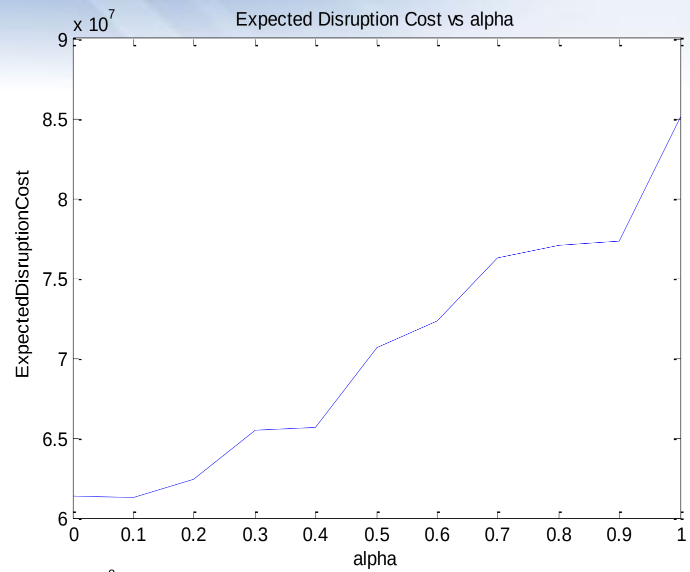
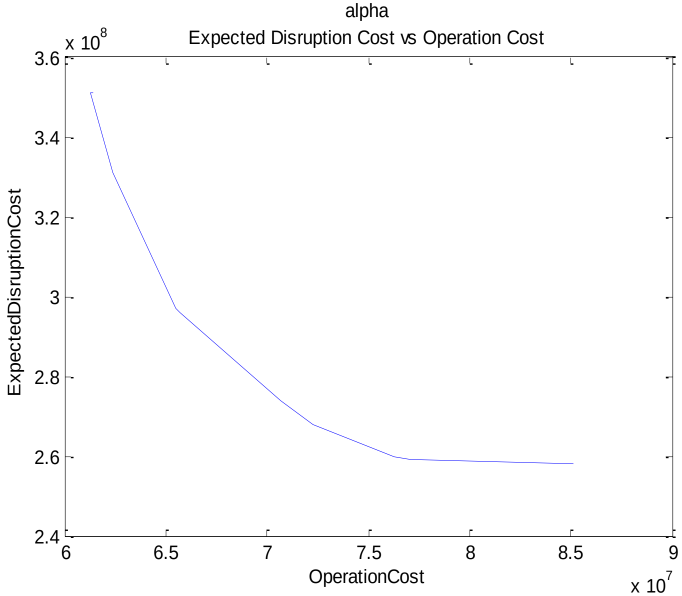
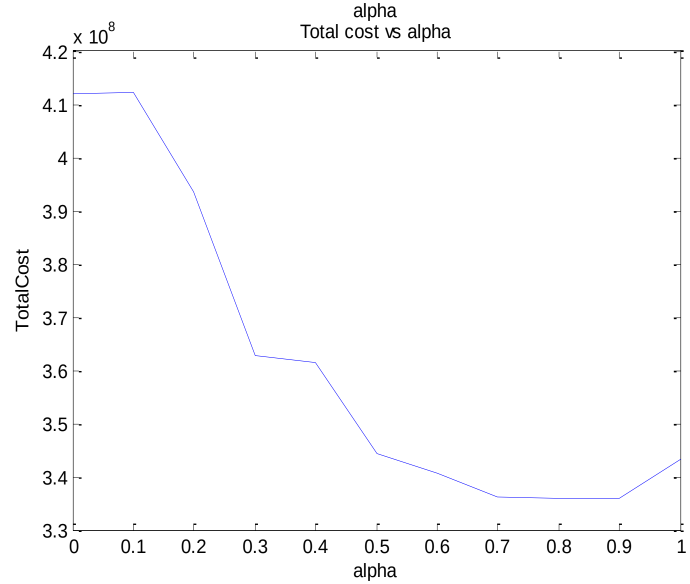
EDC and OC Trade-offs: High Volume Low Profit









Summary

- Resilient Network Design Environment
- Trade-offs between efficiency and robustness and their connection to topologies
- Re-optimize the topology when subject to disruptions for resileint control
- Python and GAMS
- Resilient Supply Chain Case Study